A silicon-cast device that aids in securing rope ends by ensuring a figure-eight knot is tied for use in gym and rock climbing

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENS FOR THE DEREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTES INSTITUTE OF TECHNOLOGY

JUNE 2008

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A silicon-cast climbing device that aids in securing rope ends by ensuring a figure-eight knot is tied for use in all forms of climbing

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Submitted to the Department of Mechanical Engineering
On May 9, 2008 in partial fulfillment of the
Requirements for the Degree of Bachelor of Science in
Mechanical Engineering

Abstract

Between the years of 1953 and 2005, there were 253 fatalities from rappel failure/error. Some of these deaths may have been prevented if a stopper knot was tied at the end of the rope. Current climbing habits do not reinforce the tying of a stopper knot. More people are learning to climb in the gym and do not know risk reducing habits when beginning to climb outside, such as tying a stopper knot. The Hedgehog is a silicon device that reinforces the risk reducing habit of tying a stopper knot by a combination of form and color. A specially designed form aids in correct knot tying and the color signals the climber their attention is needed. When the Hedgehog was given to climbers in a climbing gym and had a success rate of 70%. Climbers without the Hedgehog had a success rate of only 8%. Success was defined as having a stopper knot in the rope when the climber began to ascend the route.

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Introduction

A silicon cast knot-guiding device that prevents the rope end from slipping through a belay device would help teach better climbing practices by signaling climbers when the rope end is tied off and therefore secure. The importance of securing rope ends is evident in "Accidents in North American Mountaineering[i]" that reports 10 accidents due to rappel failure/error in the outdoors in 2007 and 252 since 1953[1]. Two of the accidents[2] involved the rope slipping through the belay/rappel device (BRD). These accidents could have been prevented if a stopper knot (Figure 1) was tied near the end of the rope. The knot stops the rope from slipping through the belay device by jamming it (Figure 2). The problem is making climbers aware off the need to secure the rope ends. My solution is to use a silicon cast knot-guiding device that will be called The Hedgehog from hereafter. The Hedgehog is a silicon device that reinforces the risk reducing habit of tying a stopper knot by a combination of form and color. A specially designed form aids in correct knot tying and the color signals the climber their attention is needed.

Figure 1: Typical rappel device setup with a figure eight stopper knot tied in the end

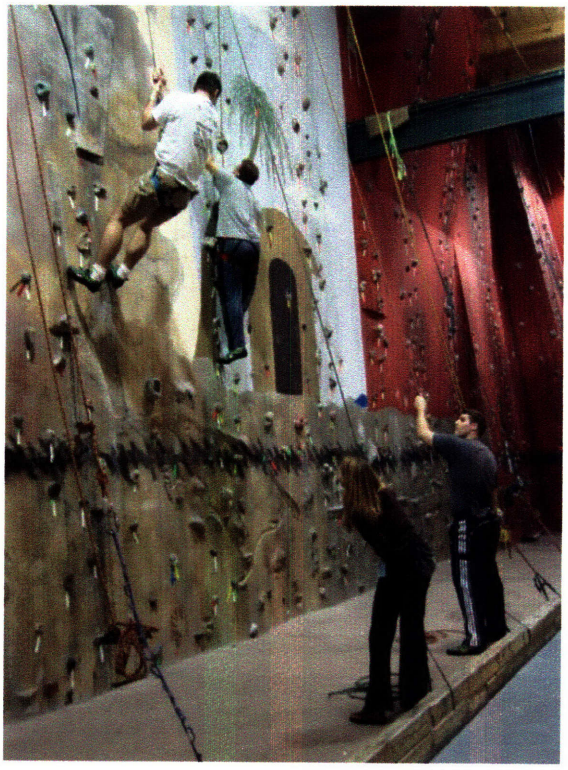
Figure 2: Figure eight stopper knot jammed in a belay device

[1] Accidents due to rappel/failure or error include many different things such as the anchor failing, incorrect use of rappelling equipment, rappelling carelessly, and many others.

[2] Not all of the accidents are written up and there may have been more cases where the rope slipped through the BRD.

Lowering and Rappelling

There are two climbing activities where rope ends need to be secured. The rope can slip two ways through a BRD while lowering or rappelling. Lowering involves a belayer and a climber (Figure 3). The climber reaches the top of the route and the belayer lowers him to the bottom. The second area in which accidents can occur is rappelling (Figure 4). This method is used by climbers to descend a cliff or route by rappel stations that someone else has placed. Both methods involve an anchor point, BRD, and a rope. These two methods of descent allow you to clean an anchor[3] and reach the ground.



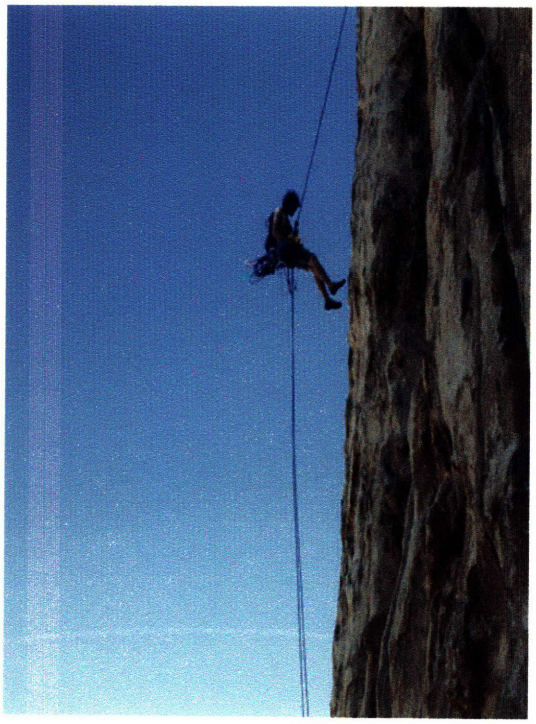


Figure 3: The climber on the left is being lowered **Figure 4: A person rappelling down a cliff-face**

[3] Cleaning an anchor involves retrieving your gear from the top of a climb so you can use it again. The bolts that you clip into are permanently left.

Lowering is one way to get off a route for most single pitch climbs that are less than half a rope length. Lowering involves a belayer and climber where the belayer is in control of the climber's descent. Figure 5 shows several scenarios that may occur during lowering. The variable in the figures is the length of the rope and accidents occur when it is not the proper length. Belayers manage the control of the descent with a BRD that gives the belayer a mechanical advantage allowing them to hold a climber with less than 100 N of force. Lowering may be done during top roping or cleaning a route.

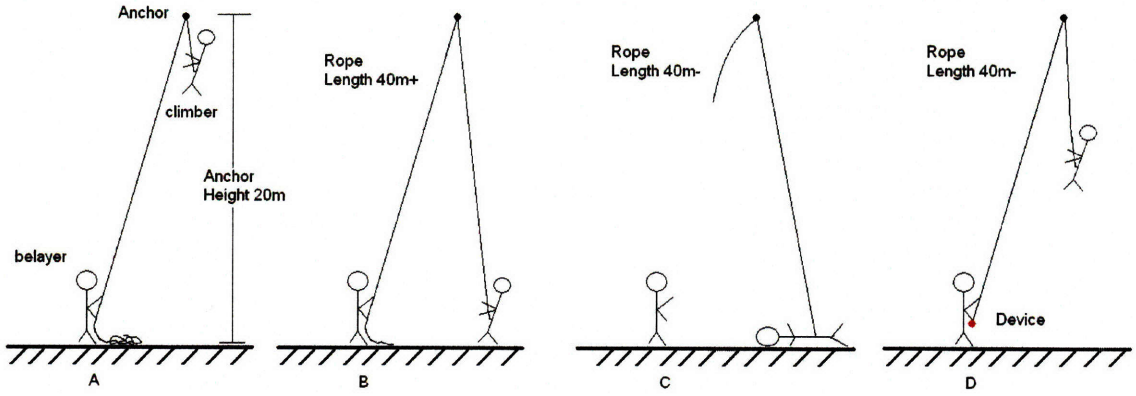


Figure 5: Possible occurrences for lowering
A) A typical configuration when the climber wishes to descend **B)** The climber safely reaches the ground **C)** The rope is too short and the climber falls to the ground **D)** The rope is too short but the Hedgehog prevents the rope from going through the BRD

A climber ascending routes that are more than a rope length may have to rappel[4] to reach the ground. Rappelling is used to descend and involves anchoring the rope at a preset Point A and then lowering yourself with a belay device to another preset Point B . Guidebooks to climbing areas give information about them but finding the rappel points on a wall after seeing them in a book is often difficult, especially if you are looking for them while you are rappelling.

Rappelling involves a BRD device, and similar frictional advantages, that allows the climber to control their descent down the rope. Ropes are made in various lengths of

[4] Rappelling also allows the climber to lower off the anchor without causing wear on it

50, 60, and 70 meters and the route length depends on the anchor setup. Figure 6 shows how rope length and configuration affect the climber's rappel.

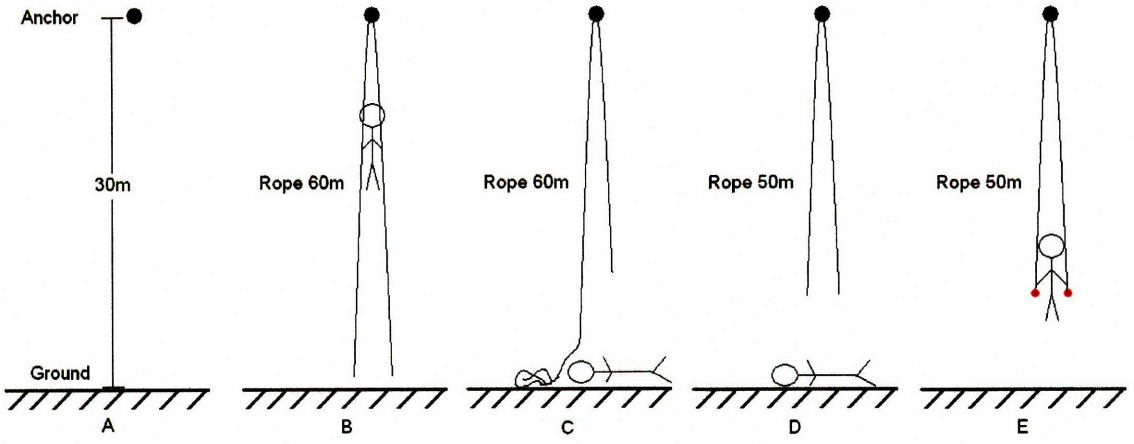


Figure 6: Possible occurrences for repelling
A) A typical configuration found on routes **B)** Correct rope length and placement
C) Correct rope length but bad placement **D)** Short rope with good placement
E) Device Placement to prevent an accident in C or D

To prevent the failure mode in which the rope end runs through the BRD the Hedgehog both ends of the rope must have knots in them. The Hedgehog will help climbers manage risks by reminding them to secure the rope ends with a correctly tied stopper knot. The red color of The Hedgehog will serve as a reminder to either the climber or their partner that the rope ends need to be secured. Rappelling may occur at the end of the day when people are tired or anxious to be finished and a small reminder can help the climber secure the rope.

Climbing Gyms vs. Outdoors

Alerting climbers to the importance of securing rope ends is of special importance when they learn how to climb in a gym. The easiest time to teach someone safety is when he or she is first learning about it. Making the transition from climbing in a gym to

climbing outside involves learning several new techniques and it is helpful to learn as many in a gym as possible. Climbing gyms are user-friendly so climbers may climb as quickly as their ability allows. Anchors are set up on climbs, the ropes are in place and of the correct length, there is no need to rappel, and staff supervision walking around to help manage risk. This can lead to a relaxed attitude regarding risk management because the gym is setup for you to climb quickly without worrying about other issues. Climbing outside requires the climber to make sure they are managing risk at all times. A climbing gym involves less rappelling than in the outdoors. If you set lead climb or top-rope in a gym, you are lowered to reach the ground. Climbing outdoors requires you to retrieve your gear from the top of a climb that necessitates rappelling.

So climbing outside involves more variables. In addition to tying in, climbing, leading, belaying, and lowering, you may have to setup an anchor, rappel, and find the route. If you learn to climb in a gym, then your exposure to rappelling is lower which may lead to mistakes rappelling outdoors if you do not get proper instructions. The Hedgehog is a means to aid in teaching techniques to help manage risk during rappelling.

Solution

The Hedgehog is designed to aid in securing rope ends by reminding people they need to tie a stopper knot and guiding them so that the stopper knot is correctly tied. If a person has learned to climb in a gym then they are less likely to be aware of all the risk management techniques. It is a different mindset when you are climbing indoors as opposed to outdoors. The Hedgehog is of particular importance to climbers that are making the transition from climbing in the gym to climbing in the outdoors.

Teach the correct initial technique of risk management during rappelling is not the main goal of the Hedgehog. People that have just learned to rappel and people that have rappelled many times still need to remember to tie the stopper knot. The knowledge of how to tie it does not mean that the climber will tie it. The bright red color of The Hedgehog will help grab climber's attention and remind them something needs to be checked, while its molded shape conforms to a properly tied figure eight and helps guide the tying.

Background

Climbing is inherently dangerous and climbing standards try to mitigate the risk wherever possible. There are requirements that some climbing gear must have to be issued in the United States, and there are some unofficial practices people follow to help reduce risk. These official and unofficial practices are what helped guide me in making my device. I also used a general guide[ii] for Product Design that allowed me to focus on the ergonomics of the Hedgehog.

Standards

There are international standards for ropes and critical climbing equipment for strength and durability. There are also unofficial standards that people seem to follow. Redundancy is used at critical points such as two bolts at an anchor. The color red also signals that a device has not been secured. Some harnesses have a strip of red on their buckle to show when you have not double backed the waist strap to secure it (Figures 3 & 4). Some locking carabineers have red on the gate when they are unlocked. Locking the carabineers causes the red strip to be covered. A review of an outdoor store, REI, found that four of their locking carabineers used a red color to signal when they gate was

unlocked. Only two harnesses showed a strip of red when they were unbuckled, this small number may be because many of the newer harnesses removes the need to buckle them.

Figure 7: A harness buckle showing red tape that has not been secured

Figure 8: A harness buckle that has been doubled back and secured

Functional Requirements

The characteristics for the Hedgehog were based primarily on its safety and then its usability. A concern during the creation of the Hedgehog was that people should not mind using it and remember to use it without becoming aggravated during climbing. Climbing involves a series of checks before belaying starts and the hope is that the Hedgehog will help climbers secure the ends of the rope as part of that checklist.

Easy to use

The Hedgehog needs to be easy to use without an instruction manual. People should be able to see it and know how to use intuitively, see row 1, Table 1. A climber should be able to pick it up after a minute figure out how it works. Actual use of the device should require less than 10 seconds. The Hedgehog was designed to fit into an

average man or woman's palm so they can hold it without discomfort. It does not require any motions to tie the knot beyond holding the rope down while the outline is followed.

Quick to inspect

The Hedgehog relies on color and interaction in order to be effective. The device is clear with a red color along the rope's path, see row 2, Table 1. With this coloring system, someone can quickly look at the Hedgehog and tell whether the figure eight is tied correctly by checking for any red spots on the device. A clear device with the rope tied around it is correctly tied. This ensures that someone does not tie a knot that could come undone when the device is loaded. The red coloring also follows similar guidelines in climbing that were mentioned above. It allows either the climber or belayer to see the device when they are performing their safety checks.

Does Not Fail

The success rate of preventing the rope ends from feeding through the BRD for the Hedgehog equals that of a regularly tied figure eight. Figure eights have been shown to hold under static loads of 1400 kg on a static rope[iii]. However, if the knot is tied with only several inches left on the end it can untie itself under stress because of rope slippage. The Hedgehog will provide extra friction in the knot to help increase the success rate. Additionally, when the figure eight knot is loaded the scorpion should not extrude into the belay device causing it to stick or otherwise rendering the belay device unusable. Row 3 table 2 shows further countermeasures for this situation.

Table 1: Design Criteria

FR	DP	Analysis	Ref.	Risks	Counter measures
Quick to use	Only one threaded point	Belayer should be able to use the device in less than 5 seconds	Past Experience	The belayer uses it incorrectly because it is quickly configured	Have a picture on the device showing how is should be used, or something similar
Easily examined	Red & Green shows when the knot is untied, only green when tied		Other climbing devices on the market	The knot can be tied incorrectly and only show green	Have a form that only configures to a figure eight knot
Does not fail	Figure eight knot should be structurally sound	Should only weaken the rope by 40% (nominal for a figure eight)	Need citation	weakens it by more than 40%	Test final product, ensure figure eight knot is not structurally changed

Prototyping

There were several stages required for the production of the prototype Hedgehog. The first step was creating a pattern that would fulfill the functions specified. It needed to take into account safety, ergonomics, and usability. Next, a material was selected that would be used for the cavity and casting of the final mold. The materials ended being used were a two-part urethane for the cavity and a two-part silicon for the mold.

Form Selection

The first decision that needed to be made was what form the Hedgehog was going to aid in people securing the end of the rope. It needed to be simple and small so the climber could carry it with them at all times, Figure 9 was an early prototype. Based on

this initial idea I concentrated on a hand held device as opposed to ground-based stations. Rappel devices similar to a prusik[5] were also excluded because of complexity and time requirements.

Figure 9: Initial prototype pattern

Designing the Form

When designing the Hedgehog shape safety was considered first and then usability. Ensuring the figure eight knot was tied correctly directed the shape of the Hedgehog. The Hedgehog is designed so that the climber must follow the outline of the rope around the device. The climber knows that the rope is tied correctly when they should only see green because the rope is covering all of the red on the device. Other methods were discarded because they were not as clear to the climber that the rope was tied correctly.

[5] A friction hitch used as a backup belay device that halts your descent if your hands leave the rope due to an accident or the need to retrieve gear from a route or other reason

The figure eight knot can be tied two different ways. Rather than dealing with both of these variations, there is an arrow and rope-guide section near the bottom of the Hedgehog. This forces the user to tie the figure eight with a right-handed chirality. The Hedgehog is designed to fit in the palm of a hand so climbers can easily hold the device and tie the knot with both hands. Keeping the knot from becoming untied relies on three retainers within the Hedgehog. There is the previously mentioned rope guide and two more edges on the bottom and top. These edges on the top and bottom are able to hold the rope because they are inset from the natural contours of the knot. There is a hole for end of the rope to be threaded. Table 2 shows the major ideas that were being considered when designing the Hedgehog.

Table 2: Prototype Criteria

FR	DP	Analysis	Ref.	Risks	Counter measures
Align Rope Chirality and placement	Short guide channel for the rope	Should not slide out under the rope's weight (~25 grams/foot)	Gri-Gri belay device	Rope falls out	"snap" into place like a tent pole
Secure end of the figure 8 knot	rope end threads through a hole	Rope should not exert enough force to deform the mold (< 800 psi shear)	regular ATC belay device	People tie the knot incorrectly	Have arrow guides that help direct the knot
Hold the form of the figure eight knot	Two lips for the top and bottom of the rope to rest on	Friction should hold the rope in place (need to test mold surface)	Ascenders	Too much friction	Smooth the areas of contact

The threaded point allows the end of the knot to be clearly marked to help ensure it is tied correctly. There are not two threaded points for the beginning and end of the knot because it takes too long to untie. Figure 10 was an early idea that required 6 threaded points and helped influence the final use of only one.

Figure 10: Early Completely threaded design

Material Selection

Silicon is used to cast the climbing device because it is lightweight, provides a static coefficient of friction of 0.4, and has a shore hardness of 40-A. The device needs to be lightweight to encourage climbers to carry it around on their harness. Enough friction is needed to ensure the knot does not slip out of the tied form. The Hedgehog should provide at least the same friction as rope on rope and preferably more to keep the knot from coming untied. A shore hardness of 40-A allows the Hedgehog to be durable and keep the load on the knot instead of the structure of the device.

Mold Creation

The pattern was made using Crayola Magic mold. This material did not give as much definition as was desired but the other alternative of modeling clay was not pliable enough for the shape. No tools were required for pattern except for a short piece of rope. The pattern dried for 24 hours before it was used to create the cavity. The cavity

compound was OOMOO 30, a platinum catalyzed two-part silicon compound. Figure 11 shows all the materials required for creating a mold.

Figure 11: Three initial designs created for possible prototyping and required materials

The pattern was secured to the bottom of a small box and both the pattern and box were sprayed with a release spray. The cavity compound was poured in around it and allowed to set for 6 hours. After setting the cavity, the pattern was removed and allowed to dry for another hour. Release spray was applied to the cavity. A silicon mixture, Sorta-Clear 40, was mixed for the mold. Vacuum degassing was used for 10 minutes to take out the air bubbles that occurred from mixing. After pouring the mold, it was allowed to sit for 16 hours before being removed.

Final Prototype

All of the prototypes were cast out of Sorta-Clear 40, a two-part silicon. The initial cavity mold was made out of OOMOO 30, a two-part silicon mixture, and the second cavity mold was made from The Hedgehog Skin, a two-part urethane mixture. The initial mold did not set well and the edges in contact with the cavity were still sticky after it had set for the required amount of time. This was probably due to both the mold and the cavity having a silicon base. The second mold was slightly sticky but after sitting in the air for 12 hours after being demolded, they finished setting. A third mold was cast with green dye but it did not cast successfully. The green dye or the age of the casting material may have caused the improper setting. The second mold was modified to look like the desired product and used for testing purposes, Figure 12. The rope fit well into the molded outline of the final design, Figure 13, and little of the coloration showed when it was properly tied. Several variations were tried where the rope was tied incorrectly and the color showed up well.

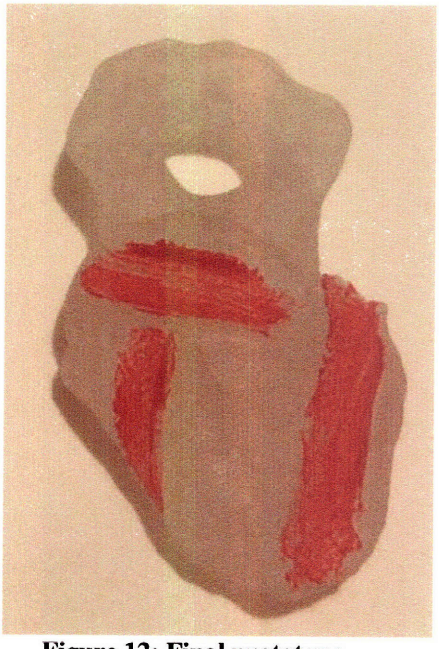


Figure 12: Final prototype

Figure 13: Final prototype with a stopper knot tied

Testing in a gym

Observing people tie figure eights without the Hedgehog at a climbing gym showed an average time of 4 seconds with 8 people.[6] These climbers were then asked to tie the figure eight using the Hedgehog[7] and had an average time of 6 seconds. Three climbers that had been climbing only once before had an average tying time of 9 seconds without The Hedgehog and 13 seconds with the Hedgehog. Observing 6 people in the gym for an hour showed only one person look at or physically check the end rope to see if a stopper knot was tied. I let three people use The Hedgehog for an hour at a time and out of 13 climbs completed, the belayer remembered to use the device 10 times. The three times it was not used was towards the end of the hour and the Hedgehog was left on the rope at the previous climb.

Conclusions

The Hedgehog had a success rate 70% between a combination of color and observance by their partners. Several times the climber remembered to tie the stopper before they started climbing. However, the majority of times either the climber or the belayer was reminded to tie the stopper knot during routine safety checks. The red color on the device may have helped grab attention but the device itself seemed to help people more. The red color may help people when they are climbing outside and climbing normally. An hour may not have been enough time to relapse into normal climbing habits.

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[6] All of the climbers had been climbing at least two times before
[7] The first three times they used the device were not counted in the above time

It was interesting to note that the Hedgehog was not used when it was forgotten at the previous climb. In the gym, this may be a problem because you are using different ropes. A way to help climbers in the gym remember the Hedgehog may be to have a colored carabineer that attaches to the Hedgehog. This way if they forget the Hedgehog they will still have the carabineer to remind them at the next climb. This seems a little excessive but in a climbing gym, there are plenty off ways to help people remember something. Climbing outside people normally have their own ropes and so this would not be a problem.

Future Work

The testing was only carried out in a climbing gym among people that were familiar with climbing. More testing would be desired among inexperienced climbers indoors and among climbers in both lowering and rappelling outdoors. It would also be interesting to see if several of the devices could be used in a climbing gym to see the effect on other people. If there were multiple devices in a climbing gym other people may start tying the stopper knot as well from others doing it.

A solid model of the pattern would be much easier to make incremental changes now the general form is finalized. It would also allow more detailed texturing and labeling of the design. The texturing of the Hedgehog where the rope touches it helps define how knot should be tied. A series of numbered arrows with labels could help guide people that are unfamiliar with tying a figure eight and it would help people that are using the Hedgehog for the first time.

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